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LATITUDINAL GRADIENTS OF GALACTIC COSMIC RAYS DURING THE 2007 SOLAR MINIMUM

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ABSTRACT

Ulysses, launched in 1990 October in the maximum phase of solar cycle 22, completed its third out-of-ecliptic orbit in 2008 February. This provides a unique opportunity to study the propagation of cosmic rays over a wide range of heliographic latitudes during different levels of solar activity and different polarities in the inner heliosphere. Comparison of the first and second fast latitude scans from 1994 to 1995 and from 2000 to 2001 confirmed the expectation of positive latitudinal gradients at solar minimum versus an isotropic Galactic cosmic ray distribution at solar maximum. During the second scan in mid-2000, the solar magnetic field reversed its global polarity. From 2007 to 2008, *Ulysses* made its third fast latitude scan during the declining phase of solar cycle 23. Therefore, the solar activity is comparable in 2007–2008 to that from 1994 to 1995, but the magnetic polarity is opposite. Thus, one would expect to compare positive with negative latitudinal gradients during these two periods for protons and electrons, respectively. In contrast, our analysis of data from the Kiel Electron Telescope aboard *Ulysses* results in no significant latitudinal gradients for protons. However, the electrons show, as expected, a positive latitudinal gradient of ~0.2% per degree. Although our result is surprising, the nearly isotropic distribution of protons in 2007–2008 is consistent with an isotropic distribution of electrons from 1994 to 1995.

Subject headings: convection — cosmic rays — diffusion — solar-terrestrial relations — solar wind

Online material: color figures

1. INTRODUCTION

The ongoing *Ulysses* mission provides a unique opportunity to study the propagation and modulation of Galactic cosmic rays (GCRs) in detail by in situ measurements in the three-dimensional heliosphere. The intensity of GCRs is modulated as they traverse the turbulent magnetic field embedded in the solar wind. These particles are scattered by irregularities in the interplanetary magnetic field and undergo convection and adiabatic deceleration in the expanding solar wind. The large-scale heliospheric magnetic field, which approximates an Archimedean spiral (Parker 1965), leads to gradient and curvature drifts of cosmic rays in the interplanetary medium. Jokipii et al. (1977) pointed out that these drift effects should also be an important element of cosmic-ray modulation. Models that take such effects into account (Evenson 1998; Heber et al. 2002; Ferreira et al. 2003a; Ferreira & Potgieter 2004) predict the latitudinal distribution of GCR protons and electrons. In the 1980s, during an $A < 0$ solar magnetic epoch, i.e., when the field is directed toward the Sun in the north polar region, models predicted a negative latitudinal gradient for positively charged cosmic rays. Such gradients were found by the cosmic-ray instruments aboard the two *Voyager* satellites (Cummings et al. 1987; McDonald et al. 1997). In the 1970s and 1990s, during the $A > 0$ solar magnetic epoch, *Pioneer* and *Ulysses* measurements from 1974 to 1977 and 1994 to 1995 confirmed the expectation of positive latitudinal gradients (McKibben 1989; Heber et al. 1996b). An overview of some selected results are given in Table 1. Because the observed latitudinal gradients were much smaller than predicted by drift-dominated models (Jokipii et al. 1977), in particular at low energies, reinvestigations emphasized the importance of stochastic and systematic perpendicular transport in the heliosphere and the modification of the heliospheric magnetic field (Fisk & Jokipii 1999; Fisk 1996). It was shown that the cosmic-ray observations could be described well when such processes were included (Ferreira et al. 2003a; Ferreira & Potgieter 2004; Potgieter et al. 1997). During the second fast latitude scan in 2000–2001, no latitudinal gradients were measured (McKibben et al. 2003; Heber et al. 2002). Thus, the importance of charge sign dependence (e.g., drift) in the diffusion process varies with the solar cycle (Ferreira et al. 2003a). When *Ulysses* again reached its highest southern heliographic latitudes in 2007, solar activity was similar to the activity level in 1994, but the heliospheric magnetic field had reversed sign.

2. INSTRUMENTATION AND OBSERVATIONS

The observations were made with the Kiel Electron Telescope (KET) aboard *Ulysses* and the Cosmic Ray Isotope Spectrometer (CRIS) aboard the *Advanced Composition Explorer* (*ACE*). KET measures protons and helium in the energy range from 6 MeV to above 2 GeV per nucleon and electrons in the energy range from 3 MeV to a few GeV (Simpson et al. 1992). *Ulysses* was launched on 1990 October 6, shortly before the declining activity phase of solar cycle 22. A swing-by maneuver at Jupiter in 1992 February placed the spacecraft into a trajectory inclined by 80° with respect to the ecliptic plane.

In this paper, we compare the *Ulysses* helium 125–250 MeV nucleon^{-1} channel with the *ACE* carbon 147–198 MeV nucleon^{-1} channel. As discussed in Gieseler et al. (2007), both channels

TABLE 1

Overview of Latitudinal Gradients for Cosmic-Ray Protons and Helium Reported in the Literature

Magnetic Epoch	Energy	G_ϑ (% deg^{-1})	Reference
$A > 0$	145–255 MeV $\mathrm{nucleon}^{-1}$ (He)	0.21 ± 0.6	McDonald et al. 1997
	145–255 MeV $\mathrm{nucleon}^{-1}$ (He) at 60 AU	0.0 ± 0.4	McDonald et al. 1997
$A < 0$	145–255 MeV $\mathrm{nucleon}^{-1}$ (He)	-1.1 ± 0.1	McDonald et al. 1997
	140–350 MeV $\mathrm{nucleon}^{-1}$ (He)	-0.8 ± 0.1	Cummings et al. 1987
	130–210 MeV (H)	-0.9 ± 0.1	Cummings et al. 1987
$A > 0$	250–2000 MeV (H)	0.29 ± 0.8	Heber et al. 1996b
	250–2000 MeV $\mathrm{nucleon}^{-1}$ (He)	0.32 ± 0.9	Heber et al. 1996b
	>2000 MeV (H)	0.17 ± 0.02	Belov et al. 1999
	>2000 MeV $\mathrm{nucleon}^{-1}$ (He)	0.12 ± 0.01	Belov et al. 1999
	>70 MeV (H)	0.04 ± 0.01	McKibben 1989
	>70 MeV (H) at 5 AU	0.4 ± 0.05	McKibben 1989

sample the same mean rigidity of about 1.2 GV and therefore allow the determination of the latitudinal gradient during the fast latitude scan from 2006 to 2008. If we assume that the temporal variation and the radial gradient are the same for electrons and protons during the fast latitude scan, the electron-to-proton ratio will mainly depend on the electron latitudinal gradients.

The top panel of Figure 1 shows *Ulysses* daily averaged count rates of 38–125 MeV protons from 1990 November to 2008 February; the middle panel shows the 78 day averaged quiet-time variation of the count rate of ~1.2 GV protons (*gray line*) together with the count rates of 1.2 GV carbon at 1 AU (*thin black line*) and electrons (*thick black line*), and the bottom panel shows ~2.5 GV electrons (*black*) and protons (*gray*). The latter two are presented as percentage changes with respect to the rates C_m measured in mid-1997 at solar minimum, $[C(t) - C_m]/C_m$. Quiet-time profiles were determined by using only time periods when the 38–125 MeV proton channel showed no contribution from solar or interplanetary particles (Heber et al. 1999). The 1.2 GV carbon

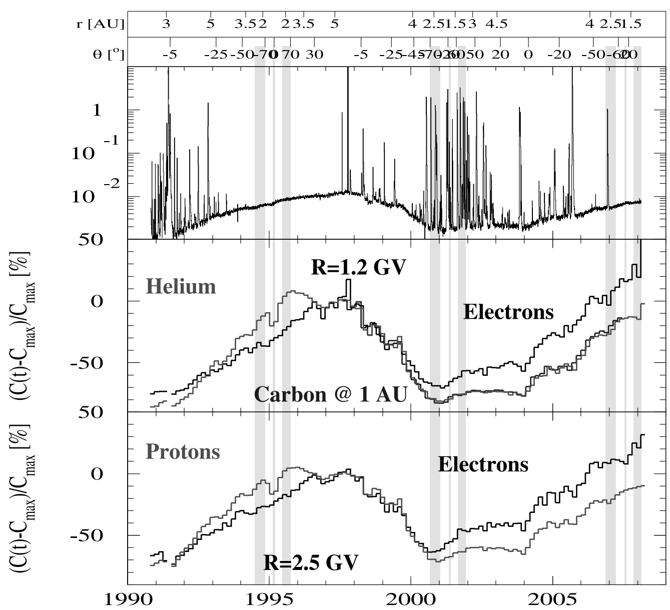

Fig. 1.— *Ulysses* daily averaged count rates of 38–125 MeV protons (*top*), 78 day averaged quiet-time variation of ~1.2 GV helium (*gray line*) compared with carbon (*thin black line*; at 1 AU) and 1.2 GV electrons (*thick black line*) (*middle*), and the ~2.5 GV electrons and protons (*bottom*) from launch in 1990 to 2008 February. *Ulysses*' distance from the Sun and its heliographic latitude are shown at the top. The three fast latitude scans are marked by shaded bands. [*See the electronic edition of the Journal for a color version of this figure*.]

data represent the temporal variation in the inner heliosphere, while the 1.2 GV helium and 2.5 GV electron and proton intensities are caused by temporal and spatial variations due to *Ulysses*' trajectory.

While the spacecraft remained close to the ecliptic, it encountered solar maximum conditions until mid-1992, as well as from 1999 to 2004, and solar minimum conditions in 1996/1997 and from 2006 to 2008, when KET registered minimum and maximum intensities, respectively. Since electrons, as well as protons, were normalized to their maximum count rates in 1997, the middle and bottom panels of Figure 1 show the relative modulation amplitude. As expected, the amplitude decreased from about 80% for 1.2 GV particles to 65% for 2.5 GV particles. The time profiles during the 1997 solar minimum were analyzed in Heber et al. (2003) and found to be consistent with the prediction of modulation models that include drift (Ndiitwani et al. 2005).

3. DATA ANALYSIS

In order to determine the latitudinal gradient of GCRs, the temporal variation and the radial gradient in the inner heliosphere at a given rigidity have to be known. We summarize some recent results important for the current analysis:

Temporal variations.—With the loss of the *IMP* satellite in 2002, no 1 AU baseline is currently available for protons above 100 MeV. Therefore, Gieseler et al. (2007) replaced these with the 125 to 250 MeV $\mathrm{nucleon}^{-1}$ helium channel and found that the 147 to 198 MeV $\mathrm{nucleon}^{-1}$ carbon channel from the CRIS instrument aboard *ACE* (Stone et al. 1998) has nearly the same temporal variation as the *Ulysses* helium channel.

Radial gradients.—Furthermore, Gieseler et al. (2007) examined the radial intensity gradient of the 125–250 MeV $\mathrm{nucleon}^{-1}$ helium channel based on the measurements mentioned above. They determined a radial gradient of $G_r = 4.7\% \pm 0.6\%\ \mathrm{AU}^{-1}$ for the 1998–2005 time period. This gradient is consistent with previous measurements (McDonald et al. 2003). The mean radial gradients of 1.2 and 2.5 GV electrons were found to be nearly the same as for protons during the declining phase of solar cycle 22 from 1992 to 1994 (Clem et al. 2002).

In what follows, we determine the latitudinal gradient of 1.2 GV helium and the latitudinal gradient of electrons at 2.5 GV from the electron-to-proton ratio.

3.1. *Latitudinal Gradient of* 1.2 GV *Helium*

Gieseler et al. (2007) showed that the 147–198 MeV $\mathrm{nucleon}^{-1}$ carbon channel of the CRIS instrument can serve as a 1 AU baseline for the 125–250 MeV $\mathrm{nucleon}^{-1}$ helium channel of KET

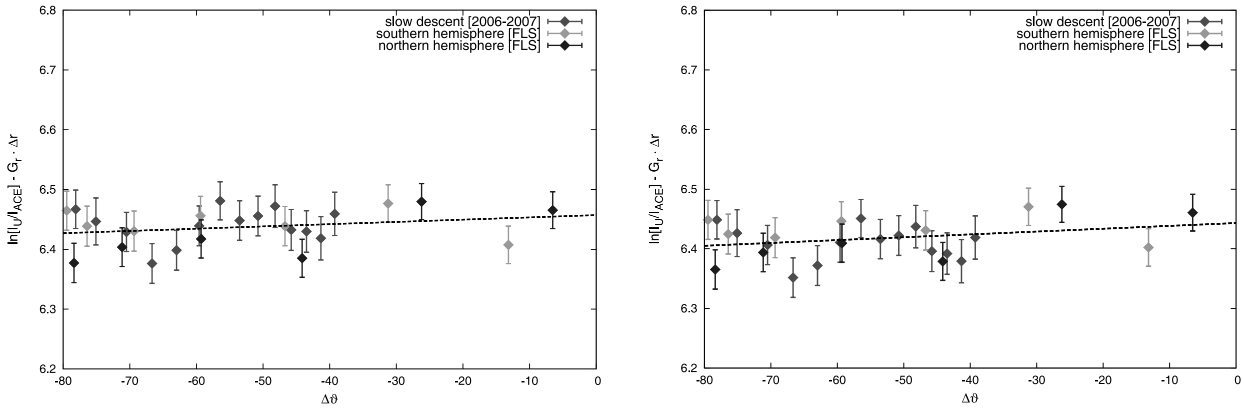

FIG. 2.—Ratio of 1.2 GV helium at *Ulysses* and 1.2 GV carbon close to Earth as a function of the latitude difference between *Ulysses* and *ACE*. Medium, light, and dark gray represent measurements during the *Ulysses* slow descend and during the fast latitude scan in the southern and northern hemisphere, respectively. *Ulysses* helium intensities have been corrected for the radial motion of the spacecraft using radial gradients of 4.1% AU^{-1} (*left*) and 5.3% AU^{-1} (*right*). [*See the electronic edition of the Journal for a color version of this figure*.]

aboard *Ulysses*. Figure 2 displays the ratio of 1.2 GV helium at *Ulysses* and 1.2 GV carbon close to Earth as a function of the latitude difference between *Ulysses* and *ACE*, $\Delta\vartheta$, assuming that the cosmic-ray distribution is symmetric around the heliographic equator. Note that we do not distinguish between northern hemisphere (*dark gray*) and southern hemisphere (*medium and light gray*) measurements. *Ulysses* helium intensities have been corrected for the radial motion of the spacecraft using radial gradients of 4.1% and 5.3% AU^{-1} as upper and lower limits on the uncertainty. It is important to note that all points are in good agreement with each other although *Ulysses* was at different locations. The lines represent the result of fitting an exponential function $I(\vartheta) = I_0 \exp(G_\vartheta \Delta\vartheta)$ to these ratios, leading to latitudinal gradients of $G_\theta = -0.04\% \pm 0.03\%\ \mathrm{deg}^{-1}$ and $G_\theta = -0.05\% \pm 0.03\%\ \mathrm{deg}^{-1}$. Within the uncertainties, these gradients are consistent with zero.

This result is surprising, because a negative latitudinal gradient was expected during the *Ulysses* 2007/2008 fast latitude scan based on the *Voyager* measurements in the 1980s (Cummings et al. 1987). Although significant positive latitudinal gradients were measured during the 1994/1995 fast latitude scan for positively charged particles (Heber et al. 1996b), the analysis of Heber et al. (2003) resulted in no significant latitudinal gradients for Galactic cosmic ray electrons.

3.2. *Latitudinal Gradient of Electrons*

The determination of latitudinal gradients for electrons is less straightforward and relies on the following assumptions:

1. The radial gradients of electrons G_r^e and protons G_r^p are the same. Since the radial distance of *Ulysses* varied between 1.4 and $\sim$2.7 AU during the fast latitude scan, a difference $G_r^e - G_r^p$ of 2% AU^{-1} would lead to an uncertainty in the latitudinal gradient of less than 0.003% deg^{-1}.

2. The temporal variations of electrons and protons are the same during the fast latitude scan. During the minimum phase of the solar cycle, the intensity time profile depends on drifts and therefore on the inclination of the heliospheric current sheet α. In the $A < 0$ solar magnetic epoch, the time profile of Galactic cosmic ray protons increases with decreasing α, while the electron intensity stays nearly constant. The Stanford group reports values between 29.4° and 33.5° using their classical line-of-sight model during the fast latitude scan.[1] Although α was constant in 2007, both time profiles of 1.2 GV electrons and protons show strong temporal variation. At slightly higher energies (2.5 GV), as displayed in the bottom panel of Figure 1 and in the top panel of Figure 3, the temporal variations are smaller. While no significant variation with latitude is observed for the 2.5 GV protons, the 2.5 GV electrons exhibit a V-shaped time profile.

3. The latitudinal gradient of 2.5 GV protons is consistent with zero. This assumption is motivated by the fact that the latitudinal gradient of 1.2 GV helium is consistent with zero and that gradients at 1.2 GV were more significant than at 2.5 GV (Cummings et al. 1987; Heber et al. 1996b).

With these assumptions, the latitudinal gradient of electrons can be estimated from the electron-to-proton ratio during the fast latitude scans around solar minimum. A latitudinal gradient of electrons should manifest itself in the electron-to-proton ratio by a V-shaped profile when the spacecraft moves from high southern to high northern latitudes (Ferreira et al. 2003b). Figure 3

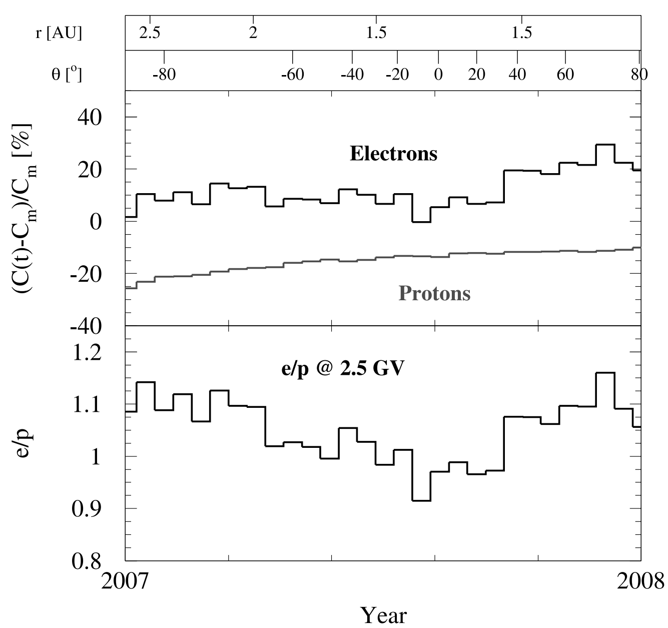

FIG. 3.—The 13 day quiet-time averages of $\sim$2.5 GV electrons and protons (*top*) and the *e*/*p* ratio (*bottom*) in 2007. The *e*/*p* ratio is higher at polar latitudes than in the ecliptic, indicating a positive latitudinal gradient of $\sim$2.5 GV electrons. *Ulysses*' distance from the Sun and its heliographic latitude are shown at the top. [*See the electronic edition of the Journal for a color version of this figure*.]

[1] See http://wso.stanford.edu/Tilts.html.

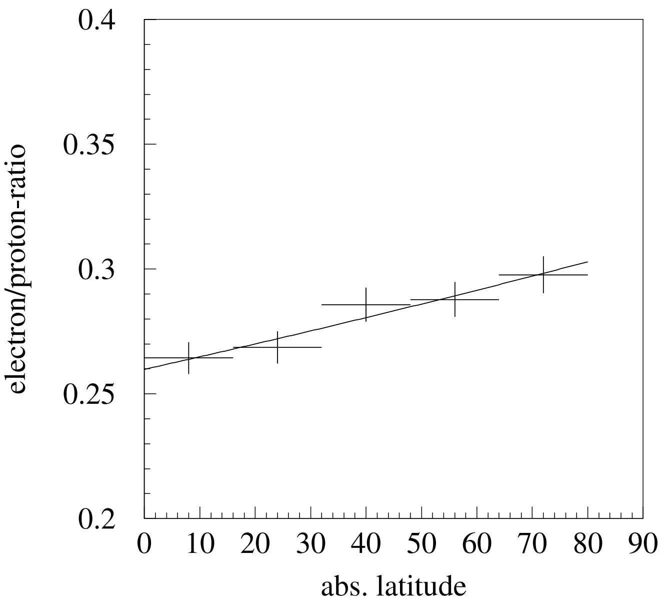

FIG. 4.— The 26 day averaged *e*/*p* ratio as a function of *Ulysses*-to-Earth latitude difference $\Delta\vartheta$, as explained in the text. The line through the data displays the fit of an exponential function with $G_\vartheta = 0.2\% \pm 0.05\%\ \mathrm{deg}^{-1}$.

displays the 13 day averaged quiet-time variation of 2.5 GV electrons and protons (*top*) and the *e*/*p* ratio (*bottom*) for 2007. The latter is lower in mid-2007, when *Ulysses* was at lower latitudes, than in early 2007 and late 2007, when the spacecraft was at southern and northern polar latitudes, confirming our expectation of a positive latitudinal gradient of electrons.

In order to determine this gradient, Figure 4 shows the *e*/*p* ratio as a function of the latitude difference, $\Delta\vartheta$, between *Ulysses* and Earth, calculated as

$$\Delta\vartheta = \left|\left|\vartheta^U\right| - \left|\vartheta^A\right|\right| \quad (1)$$

with ϑ^U and ϑ^A the latitudes of *Ulysses* and *ACE*, respectively. Thus we assume that the Galactic cosmic ray electron distribution is symmetric around the heliographic equator. In contrast to Heber et al. (1996a) and Simpson et al. (1996), the data do not us allow to investigate the north-south asymmetry found during the first fast latitude scan. In order to achieve reasonable statistical accuracy, the data in Figure 4 are binned by 15°. The solid line displays the result of a fit of the form

$$\frac{e}{p}(\Delta\vartheta) = \frac{e}{p}\exp\left(G_\vartheta \Delta\vartheta\right), \quad (2)$$

resulting in a latitudinal gradient of $G_\vartheta = 0.2\% \pm 0.05\%\ \mathrm{deg}^{-1}$ for electrons. Heber et al. (1996b) found a latitudinal gradient G_ϑ of $0.29\% \pm 0.08\%\ \mathrm{deg}^{-1}$ for 2.5 GV protons during the first fast latitude scan. Thus, the electron gradients found during the third fast latitude scan are consistent with the small gradients of protons during the first scan.

4. SUMMARY AND CONCLUSION

The large-scale heliospheric magnetic field causes gradient and curvature and current sheet drifts. When the field is directed outward from the Sun in the north polar region ($A > 0$) as in the 1990s, drift models predict that positively charged particles drift predominantly inward through the solar polar regions and then outward through the equatorial regions along the heliospheric current sheet. In contrast, electrons drift mainly into the inner heliosphere along the heliospheric current sheet and then outward through the polar regions. The vanishing and small positive latitudinal gradients for electrons and protons during the 1997 solar minimum can be understood in terms of modulation models that take into account larger perpendicular diffusion to the mean heliospheric magnetic field than previously expected. After solar magnetic field reversal, these patterns reverse. Therefore we investigated the GCR latitudinal gradients obtained in *Ulysses*' fast latitude scan during 2007. If we correct the 1.2 GV helium data with a radial gradient of $G_r = 4.7\% \pm 0.6\%\ \mathrm{AU}^{-1}$ for *Ulysses*' radial variation, we obtain a latitudinal gradient $G_\vartheta = -0.04\% \pm 0.03\%\ \mathrm{deg}^{-1}$. These values are in agreement with the vanishing gradient of electrons during the $A > 0$ solar magnetic epoch.

The determination of the electron gradient is less straightforward and relies on the assumption that the radial gradient and temporal variation of electrons and protons are nearly the same in 2007. In 2007, the temporal recovery of 1.2 GV particles was still much larger than the latitudinal variation, so we used the 2.5 GV electrons and protons instead. Our analysis results in a latitudinal gradient $G_\vartheta = 0.2\% \pm 0.05\%\ \mathrm{deg}^{-1}$ for electrons. Although the uncertainty is quite large, we can for the first time determine the latitudinal distribution of Galactic cosmic ray electrons during an $A < 0$ solar magnetic epoch. Our result is consistent with that for GCR protons in the 1990s during the $A > 0$ solar magnetic epoch. Since these gradients are much smaller than would be predicted without an enhanced perpendicular transport, we conclude that the cause of such an enhancement is present in the $A > 0$ and $A < 0$ solar magnetic epochs. Since there are two competing models to explain such particle transport, our results might help to distinguish between these numerical particle transport models.

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REFERENCES

Belov, A. V., et al. 1999, Adv. Space Res., 23, 443
Clem, J., Evenson, P., & Heber, B. 2002, Geophys. Res. Lett., 29(23), No. 2096
Cummings, A. C., Stone, E. C., & Webber, W. R. 1987, Geophys. Res. Lett., 14, 174
Evenson, P. 1998, Space Sci. Rev., 83, 63
Ferreira, S. E. S., & Potgieter, M. S. 2004, ApJ, 603, 744
Ferreira, S. E. S., Potgieter, M. S., & Heber, B. 2003a, Adv. Space Res., 32, 645
Ferreira, S. E. S., Potgieter, M. S., Heber, B., & Fichtner, H. 2003b, Ann. Geophys., 21, 1359
Fisk, L. A. 1996, J. Geophys. Res., 101, 15547
Fisk, L. A., & Jokipii, J. R. 1999, Space Sci. Rev., 89, 115
Gieseler, J., Heber, B., & Müller-Mellin, R. 2007, Proc. 30th Int. Cosmic-Ray Conf. (Mérida), http://dpnc.unige.ch/ams/ICRC-07/icrc0354.pdf
Heber, B., Clem, J. M., Müller-Mellin, R., Kunow, H., Ferreira, S. E. S., & Potgieter, M. S. 2003, Geophys. Res. Lett., 30(19), No. 8032
Heber, B., Dröge, W., Kunow, H., Müller-Mellin, R., Wibberenz, G., Ferrando, P., Raviart, A., & Paizis, C. 1996a, Geophys. Res. Lett., 23, 1513
Heber, B., et al. 1996b, A&A, 316, 538
———. 1999, Geophys. Res. Lett., 26, 2133
———. 2002, J. Geophys. Res., 107(A10), No. 1274
Jokipii, J. R., Levy, E. H., & Hubbard, W. B. 1977, ApJ, 213, 861
McDonald, F. B., Fujii, Z., Heikkila, B., & Lal, N. 2003, Adv. Space Res., 32, 633
McDonald, F. B., et al. 1997, J. Geophys. Res., 102, 4643

McKibben, R. B. 1989, J. Geophys. Res., 94, 17021
McKibben, R. B., et al. 2003, Ann. Geophys., 21, 1217
Ndiitwani, D. C., Ferreira, S. E. S., Potgieter, M. S., & Heber, B. 2005, Ann. Geophys., 23, 1061
Parker, E. N. 1965, Planet. Space Sci., 13, 9
Potgieter, M., Haasbroek, L., Ferrando, P., & Heber, B. 1997, Adv. Space Res., 19, 917
Simpson, J. A., Zhang, M., & Bame, S. 1996, ApJ, 465, L69
Simpson, J. A., et al. 1992, A&AS, 92, 365
Stone, E. C., et al. 1998, Space Sci. Rev., 86, 285